The positron density in the intergalactic medium and the galactic 511 keV line

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The 511 keV electron-positron annihilation line, most recently characterized by the INTEGRAL/SPI experiment, is highly concentrated towards the Galactic centre. Its origin remains unknown despite decades of scrutiny. We propose a novel scenario in which known extragalactic positron sources such as radio jets of active galactic nuclei (AGN) fill the intergalactic medium with MeV e^+e^- pairs, which are then accreted into the Milky Way. We show that interpreting the diffuse cosmic radio background (CRB) as arising from radio sources with characteristics similar to the observed cores and radio lobes in powerful AGN jets suggests that the intergalactic positron-to-electron ratio could be as high as $\sim 10^{-5}$, although this can be decreased if the CRB is not all produced by pairs and if not all positrons escape to the intergalactic medium. Assuming an accretion rate of one solar mass per year of matter into the Milky Way, a positron-to-electron ratio of only $\sim 10^{-6}$ is already enough to account for much of the 511 keV emission of the Galaxy. A simple spherical accretion model predicts an emission profile highly peaked in the central bulge, consistent with INTEGRAL observations. However, a realistic model of accretion with angular momentum would likely imply a more extended emission over the disk, with uncertainties depending on the magnetic field structure and turbulence in the galactic halo.

The long-standing problem of the origin of the Galactic 511 keV line remains unsolved, four decades after its first detection. Observations by the INTEGRAL/SPI experiment imply the annihilation of at least $\sim 2 \times 10^{43}$ positrons per second, mainly from a spherical bulge at the galactic centre subtending an angle of $\sim 10^\circ$ in the sky [1, 2]. The bulge-to-disk ratio of luminosities from e^+e^- annihilation is ~ 1.4 [3] and the ratio of the 511 keV line to the lower energy continuum is consistent with 100% annihilation via positronium formation [4].

Positrons are copiously produced in astrophysics. Stellar nucleosynthesis and supernova explosions produce radioactive nuclides that decay via β^+ emission, resulting in MeV–scale positrons. High-energy particles, either photons or cosmic rays, can produce $\gg$ MeV positrons via pair production or pion decay. The rate of positron production in the Milky Way has been estimated for a number of candidate sources, but none reproduce the correct morphology (see [5] for a comprehensive review). Positrons produced by these sources can travel long distances before annihilating, reducing the correlation between the distribution of sources and the detection pattern, although this does not lead to any concentration of the signal in the bulge [6]. In light of the difficulties to explain the properties of the Galactic 511 keV emission with astrophysical sources, annihilation or decay of dark matter has been invoked as an alternative source of positrons and as an explanation of the large contribution from the bulge (*e.g.* [5, 7, 8]).

This paper discusses a novel possibility. Positrons that escape from their source and their host galaxy in jets or winds may reach the intergalactic medium (IGM) to stay there indefinitely, as long as their cooling time remains longer than the age of the universe. Positrons of very high energy ($E \gtrsim 100(1+z)^{-5/2}$ MeV at redshift z) are slowed by Compton scattering with the CMB, and positrons of very low energies (highly subrelativistic) cool by Coulomb scattering with thermal electrons. At intermediate energies, however, positrons do not cool over the age of the universe in the IGM. The turbulent magnetic structure of the escaping jets and winds can furthermore trap the pairs, forcing them to follow the motion of the plasma fluid as long as the magnetic field has enough small-scale structure to prevent particles from diffusing over large distances by moving along the field lines. Positrons fill the IGM, and if they are eventually accreted by gravity wells such as our own galaxy, they annihilate whenever they reach a medium with high enough density to cool by Coulomb scattering (e.g., [9]).

To the best of our knowledge, the intergalactic positron abundance produced by astrophysical sources has not been previously considered. In this letter, we estimate the intergalactic positron density and show that positrons accreted by the Milky Way may substantially contribute to the Galactic 511 keV emission line. We first estimate the IGM positron-to-electron ratio based on cosmic radio background (CRB) observations, assuming that the radio signal is produced in sources similar to the observed active galactic nuclei (AGN) jets and radio lobes. We then compute the expected 511 keV line luminosity and the emission profile in a spherical accretion model. We find that the annihilation in this spherical model happens mostly in the galactic bulge as required by observations. We conclude with a discussion of the expected changes of the emission profile in a more realistic accretion model as well as the potential of new radio observations of the

small scale fluctuations to test our hypothesis.

The CRB has been measured from 0.01 to 90 GHz by several collaborations including, most recently, the ARCADE-2 experiment [10]. The observed brightness temperature spectrum, in excess of the constant cosmic microwave background (CMB) and corrected for Galactic emission, is well fitted by a power-law:

$$T_{\rm radio} = (1.26 \pm 0.09{\rm K}) \left(\frac{\nu}{\rm GHz}\right)^{-2.6\pm0.04} . \quad (1)$$

The shape of the spectrum is reproduced by synchrotron emission [11, 12] from a population of electrons and positrons with a power-law distribution of energies $E = \gamma m_e c^2$, $n_p(\gamma)\, d\gamma \propto \gamma^{-p}\, d\gamma$, with an index $p = 2.2$. Extrapolations from luminosity functions of known synchrotron-emitting sources account only for about one sixth of the observed background intensity [11]. Underestimating the level of Galactic emission is a potential contaminant [13]. However, the expected contribution is determined with tight errors, 5 (0.4) mK at 3.3 (10) GHz, compared to the CRB brightness temperature of 54 (3) mK at the same frequencies.

The brightness temperature in equation (1) corresponds to an energy density per unit frequency, u_ν, of

$$\begin{aligned} \nu\, u_\nu &= \frac{8\pi\nu^3 k_B}{c^3} T_{\rm radio} \\ &= (1.0 \pm 0.1) \times 10^{-7} \left(\frac{\nu}{1\,{\rm GHz}}\right)^{0.4} {\rm eV\ cm^{-3}} . \quad (2) \end{aligned}$$

Pairs with a Lorentz factor γ radiating synchrotron in a magnetic field B, with Larmor frequency $\omega_B = eB/(m_e c)$, dominate the emitted power at an emitted frequency $\nu_e = A\gamma^2\omega_B$ and have a synchrotron cooling time $t_c = 9c/(4\gamma r_e \omega_B^2)$. Here, r_e is the classical electron radius and A is a constant close to unity, which we use to match the integrated energy density in pairs to the photon luminosity at a given frequency (see equation 4 below). We assume an approximately constant magnetic field, and we define t_e as the time over which pairs in a radio source radiate via synchrotron emission. This roughly corresponds to the lifetime of the source. During this time, pairs with Lorentz factor γ will have radiated a fraction t_e/t_c of their rest mass energy. This may be used to relate the average number density of radiating pairs with energy $\gamma m_e c^2$ at a mean source redshift $(1 + z_r)$ to the present comoving energy density of emitted synchrotron photons:

$$n_p(\gamma) d\gamma = \frac{u_\nu d\nu (1 + z_r)}{2\gamma m_e c^2} \, \frac{t_c}{t_e} \, f_I \, , \quad (3)$$

where f_I is the fraction of contributing pairs that were able to escape to the IGM, and the observed frequency is $\nu = \nu_e/(1 + z_r)$. Note that t_e/t_c is much less than unity for low-γ pairs that radiate only a small fraction of their energy to the radio background, and can be larger than one for very high γ, when pairs need to be reaccelerated many times within a source in order to maintain the emitted power-law spectrum. Now, using $u_\nu \propto \nu^{-(p-1)/2}$ and $\gamma = [\nu(1 + z_r)/(A\omega_B)]^{1/2}$, and computing the total number density of pairs $N_p = n_p(\gamma)\gamma^p/[(p-1)\gamma_{min}^{p-1}]$ integrated for all $\gamma > \gamma_{min}$, we infer from equation (3) that

$$N_p = \frac{\nu u_\nu}{m_e c^2} \left(\frac{A\omega_B}{\nu}\right)^{\frac{3-p}{2}} \frac{9c\, f_I (1 + z_r)^{\frac{p-1}{2}}}{4(p-1) r_e \omega_B^2 t_e \gamma_{min}^{p-1}} . \quad (4)$$

This relationship tells us that the number density of pairs is equal to the energy density per unit $\log\nu$ in the radio background divided by the electron rest-mass energy, times a number of dimensionless factors. Note that N_p is independent of the frequency ν at which we choose to evaluate it, because $\nu u_\nu \propto \nu^{(3-p)/2}$. The uncertainties are the magnetic field, the emission time t_e, the mean source redshift z_r and the escape fraction f_I. The factor γ_{min} should be close to unity in the source rest-frame for a realistic mechanism to accelerate the synchrotron emitting particles.

Using typical values for the lobes of radio-loud AGN of $B \sim 10\,\mu$G and $t_e \sim 10^{7.5}$ yr (assuming that radio lobes expand at the typical intracluster sound speed), replacing $p = 2.2$ and using $z_r = 1$ and $A = 1$, and dividing by the mean electron density in the universe at present, $\bar{n}_e = 2.3 \times 10^{-7}\,{\rm cm}^{-3}$ [14], we obtain the IGM positron-to-electron ratio:

$$N_p/\bar{n}_e = 1.6 \times 10^{-5} \left(\frac{B}{10\,\mu{\rm G}}\right)^{-1.6} \frac{10^{7.5}\,{\rm yr}}{t_e} \frac{f_I}{\gamma_{min}^{1.2}} . \quad (5)$$

Thus, for typical parameters of a radio lobe, $N_p/\bar{n}_e \simeq 10^{-5} f_I$. For the core regions of AGN jets there is an additional Doppler factor of $\delta = [\Gamma(1 - \beta\cos\theta)]^{-1}$ in the observed luminosity due to relativistic beaming, where Γ is the jet bulk Lorentz factor and θ is the angle between the jet and the line of sight. Equation (5) is then modified with a factor $\delta^{-\frac{5-p}{2}}$. The typical value of the magnetic field in the core of AGN jets is $B \sim 3\,$mG, as estimated from a sample of resolved sources [15] showing a characteristic spectrum of synchrotron radiation and self-absorption [16]. For the same sources $\delta \sim 8.5$ and the emission time is the light-crossing time of the core region, $t_e \sim 25\,$yr. We obtain the IGM positron-to-electron ratio $N_p/\bar{n}_e \sim 10^{-5} f_I$. Note that many radio jets may be produced in isolated galaxies without a massive intracluster medium surrounding them, so the relativistic jet may be directly expelled to the IGM without producing observable radio lobes.

We conclude here that if most of the CRB were generated by electron-positron pairs in sources similar to the AGN jets and radio lobes (with similar values of $B^{1.6} t_e$), and if most of the positrons contained in these sources eventually escaped to the IGM, then there would be about ten positrons for every million electrons in the

universe. This fraction may be much lower if the radio background is mostly produced by electrons rather than pairs, or from sources with high values of $B^{1.6}t_e$ compared to AGN, or if most of the positrons do not escape. We note that these energetic particles would contribute to the matter pressure of the IGM. The ratio of the energetic particles pressure to the thermal IGM pressure is $\sim N_p m_e c^2/(\bar{n}_e k_B T_I) \sim 5$, for $T_I = 10^4$ K and $N_p/\bar{n}_e \sim 10^{-5}$, so for the maximum value of the positron abundance the pressure would appreciably modify the IGM dynamics determining the properties of the Lyα forest.

Such a large e^+ fraction could lead to a visible annihilation signal as these positrons are accreted into galaxies with other intergalactic matter. In fact, if our galaxy is accreting matter at a rate $\dot{M}$, the number of positron annihilations implied is $10^{49.5}\,(N_p/\bar{n}_e)\,\dot{M}/(M_\odot\,\mathrm{yr}^{-1})\,\mathrm{s}^{-1}$. For the Milky Way, we can expect a gas accretion rate of $\sim 1\,M_\odot\,\mathrm{yr}^{-1}$ [17], and reproducing the observed INTEGRAL 511 keV luminosity implying an annihilation rate of $2\times10^{43}\,\mathrm{s}^{-1}$ therefore requires $N_p/\bar{n}_e \sim 10^{-6}$, which is safely below our estimated maximum and can be matched by assuming $f_I \sim 10^{-1}$.

Next, we model the distribution of the 511 keV emission from spherically symmetric accretion of plasma containing relativistic positrons. The dominant contribution to the positron cooling rate is due to Coulomb scattering, and is roughly proportional to the density of electrons in the interstellar medium (at high positron energies, the cooling rate does not depend much on whether the electrons are in ionized, atomic or molecular matter). A positron with an initial energy E_{IGM} before infall will annihilate when it reaches a region of high enough density for it to efficiently thermalize; this location depends on the matter distribution and the energy E_{IGM}.

We parameterize the matter distribution in the Milky Way as an axially symmetric distribution of matter, using a model that compiles the results of several observation studies described in detail in Ref. [18]. The height-dependence of the HI and H_2 densities is Gaussian, with scale heights of 250 pc and 70 pc, respectively. The HI density on the galactic plane at our location is ~ 1 atom cm^{-3}, whereas H_2 is in a molecular ring around a galactocentric radius of $R = 5\,$kpc, with a peak density on the plane of $\sim 2.5\,$atom cm^{-3}. The HII distribution has two components, a central exponential disk with a scale height of 1 kpc and central density of 0.025 atom cm^{-3}, and an annulus around $R = 2\,$kpc representing HII regions, with a scale height of 150 pc and peak density of 0.2 atom cm^{-3}. We use the energy loss-rates computed with the GALPROP package [19, 20], which also includes the subdominant effects of inverse-Compton scattering of CMB and interstellar light, bremsstrahlung, synchrotron radiation and ionization. Details of the exponential magnetic field model and the interstellar radiation field used to compute these are also in Ref. [18] and references therein.

The positrons are initially distributed in a power law with index of -2.2, following the inferred synchrotron-producing spectrum from the CRB, with lowest energy of 1 MeV. We have checked that decreasing the index to -2.5 (as in spectra observed in most AGNs) has little quantitative impact. Note also that positrons of very high energy should have cooled below ~ 10 MeV in the IGM by Compton scattering, although these are a minority of the particles and it also has little impact on the computed annihilation distribution. The calculation of energy loss is stopped when positrons reach energies below 100 eV, at which point thermalization and annihilation should quickly follow. The flux of 511 keV photons can then be found from the annihilation rate per unit volume $dN_{e^+}/dVdt$:

$$\mathrm{d}\Phi_{511} = 2\frac{\mathrm{d}\Omega}{4\pi}\int_{\mathrm{l.o.s.}}\frac{1}{4}\frac{dN_{e^+}}{dVdt}(x)\mathrm{d}x, \tag{6}$$

where x is the direction along the line of sight (l.o.s.), the prefactor of 2 accounts for the two outgoing photons per annihilation and the 1/4 accounts for the fact positronium decay to two photons only occurs when para-positronium is formed, one quarter of the time.

The results are then compared with the INTEGRAL/SPI observations. Figure 1 shows a comparison between measured and predicted flux in the inner 16 degrees of latitude (upper panel) and longitude (lower panel). These figures illustrate that the spherical accretion model allows us to reproduce the large annihilation signal from the bulge. Using the parametrization of Ref. [2], we obtain a bulge-to-disk ratio of 2.6, leaving room for annihilations from Al^{26} produced in supernovae and other β^+-producing isotopes distributed in the disk.

Spherical accretion concentrates the infalling positrons close to the Galactic centre, producing a bright annihilation region in the bulge. A more realistic model would allow for the IGM gas to carry angular momentum and for a non-spherical galactic potential, so the gas could then fall over a much larger area around the disk. This would redistribute the luminosity over the disk, reducing the central luminosity and smearing the small-scale features. The positrons annihilate at the point where the medium is dense enough for them to lose sufficient energy, and this may often occur in disk crossings rather than near the bulge. However, the details depend on the way the structure of the magnetic field in the Galaxy halo may modify the trajectories of accreting IGM plasma. Previous studies have considered a possible focusing effect of a dipole magnetic field lines of the halo, although there has not been direct observation of such a dipole component [5, 21]. Nevertheless, if such a dipole field is present, it could contribute to an enlarged positron density in the bulge. This is clearly a complex problem that we cannot address in this letter. We note also that if the extragalactic positrons contribute substantially to

the total annihilation signal but in a more extended fashion, the concentration to the bulge might also be caused by recent AGN activity from the central black hole in the Milky Way having delivered positrons to the bulge region.

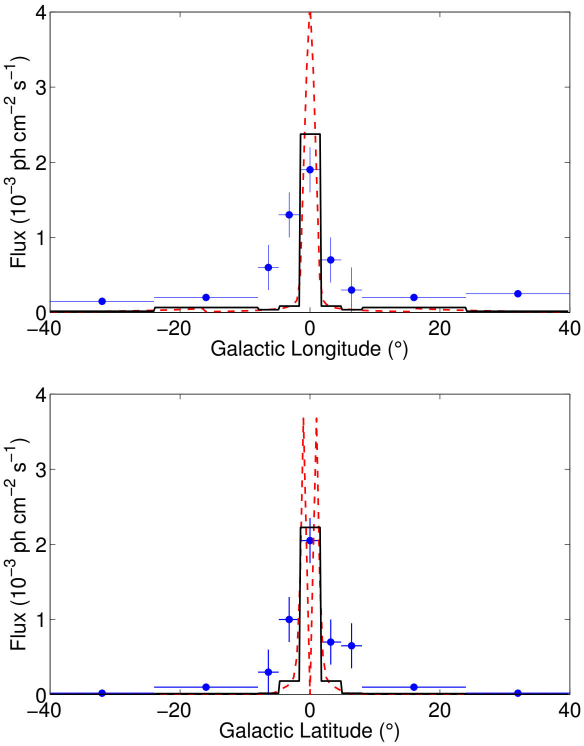

FIG. 1: *The binned INTEGRAL/SPI 511 keV data from [3], integrated over* $|\text{Latitude}| < 8^\circ$ ($|\text{Longitude}| < 8^\circ$)*, is shown by the data points in blue in the upper (lower) panel. The outer four bins are* 16° *wide, and inner bins are* 3.2° *wide. Black solid line shows the predicted flux in the spherical infall model, binned in the same way. The red dashed line shows the shape of the predicted flux, with its area matching the normalization of the histogram.*

The sources of the CRB are still unknown. It has recently been argued [22] that the RMS fluctuations of the CRB are more than an order of magnitude smaller than those of the infrared background. If cosmological, the sources for the radio background might be either at high redshift or spatially extended (on Mpc scales), so that the clustering amplitude is substantially lower. Alternatively, the radio sources might not be highly biased, for example if they arise from a population of low-luminosity AGN in low-mass halos, and this would reduce their clustering. The new generation of radio observations, measuring the small scale fluctuations of the background, would be able to test whether the cosmological population of AGN cores and lobes are sourcing the radio background. We note that there might be positrons injected in the IGM at redshifts higher than ~ 6, which would Compton-cool to non-relativistic energies in the IGM before they are accreted to a galaxy, so that at present they would annihilate at lower gas densities leading to a 511 keV emission extending to higher galactic latitude than observed by INTEGRAL.

In summary, we have presented a new possible source of positrons that can contribute to the 511 keV emission from the Milky Way: the accretion of intergalactic material containing positrons that have been produced over the age of the universe in high-luminosity objects that can expel matter to the IGM, such as the jets of active galactic nuclei. Based on the radio background intensity, we have obtained their $e^{\pm}$ contribution to the IGM using Eqs. (4) and (5). If the CRB comes from these synchrotron-emitting sources, we estimate a maximum density of 10^{-5} positrons per electron in the IGM. The positron fraction required to produce the observed INTEGRAL 511 keV luminosity is $\sim 10^{-6}$, well below our maximum estimation. The main feature of the INTEGRAL/SPI observation, namely the large density of positrons in the Galactic bulge, can be reproduced by a simple spherical model of accretion, although a prediction of the exact line emission morphology will require more realistic modelling of IGM gas accretion and of the magnetic field structure in the Galactic halo.

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